

Radial velocity variations of the pulsating subdwarf B star PG 1605+072[★]

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ABSTRACT

We present an analysis of high-speed spectroscopy of the pulsating subdwarf B star PG 1605+072. Periodic radial motions are detected at frequencies similar to those reported for photometric variations in the star, with amplitudes of up to 6 km s^{-1} . Differences between relative strengths for given frequency peaks for our velocity data and previously measured photometry are probably a result of shifting of power between modes over time. Small differences in the detected frequencies may also indicate mode-shifting. We report the detection of line-shape variations using the moments of the cross correlation function profiles. It may be possible to use the moments to identify the star's pulsation modes.

Key words: stars: individual: PG 1605+072, stars: subdwarfs, stars: oscillations, stars: variables: other

1 INTRODUCTION

It has been several years since the announcement of the discovery that some subdwarf B stars pulsate (Kilkenny et al. 1997). Photometric variations in sdBV stars, or “EC 14026 stars” after the prototype, are measured in hundredths of a magnitude and generally have periods of 100–200 s. They appear to be due to low-order stellar pulsations. When the pulsations are better understood, it will be possible to use asteroseismology to obtain more information about the stars, including their size, mass, and structure, as has been done with some other classes of pulsating stars. This will probably require multi-site photometric and spectroscopic observations.

PG 1605+072 has the largest photometric pulsation amplitudes and the richest frequency spectrum of all studied sdBV's. Its light curve shows more than 50 frequencies, though it is dominated by 5 frequencies between 1.89 and 2.74 mHz (periods between 529 and 365 s) (Koen et al. 1998; Kilkenny et al. 1999). It has an effective temperature of $32\,300 \pm 300 \text{ K}$ (Heber, Reid, & Werner 1999). It has a lower gravity ($\log g = 5.25$) and longer pulsation periods than any other sdBV studied, which Kilkenny et al. (1999)

say indicates that it has evolved away from the core helium burning horizontal branch where the shorter-period sdBV's are found. It is expected to be evolving more rapidly than other known sdBV's.

Kawaler (1999) and Kilkenny et al. (1999) report comparisons of the large-amplitude pulsations of PG 1605+072 to those of a model with similar physical parameters. They suggest that what are observed are most likely low-order nonradial pulsations in “trapped modes,” though it was not possible to make individual mode identifications.

An earlier study, O'Toole et al. (2000), used time-resolved spectroscopy of PG 1605+072 to look for evidence of pulsation in the radial velocities. Their observations provided 38.65 hours of data over a 10 day period. Spectra within a data series were generally separated by 61 to 75 seconds. They detected velocity variations, with the three largest amplitudes having frequencies similar to those found in the photometric data by Kilkenny et al. (1999). The combination of the fairly slow repetition of observations, noise in the velocity spectrum caused by the use of small diameter ($< 2\text{-m}$) telescopes, and a broad observational alias signature in comparison with the spacing of the frequencies observed in the photometry meant that only the strongest pulsations could be detected with any certainty.

We report the results of two-site spectroscopic observations of PG 1605+072. We take advantage of the higher signal to noise spectra and faster readout repetition possible with the 4-m class Anglo-Australian (AAT) and William Herschel (WHT) telescopes to provide radial velocities for a study of the star's pulsations. Previous work has shown that

[★] Based on observations made with the Anglo-Australian Telescope, Coonabarabran, NSW, Australia and the William Herschel Telescope operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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high speed spectroscopy at the WHT can be used to detect even small amplitude radial motions, $\sim 2 \text{ km s}^{-1}$, in sdBVs (Jeffery & Pollacco 2000).

2 OBSERVATIONS AND REDUCTION

We obtained spectra of PG 1605+072 at a high time resolution (13 to 22 second repetition) using the 3.9-m AAT and the 4.2-m WHT on the nights of 11 and 12 May 2000. Using both telescopes allowed us to obtain a more continuous data set than possible with a single site. We obtained 16.3 hours of data over a 32.1 hour period. Spectra from both sites covered a 400 \AA range chosen to include the $H\delta$ and $H\gamma$ Balmer lines.

The data were reduced using scripted standard IRAF routines to make the bias, flat-field, and sky corrections, extract the one dimensional spectra, and to apply the wavelength calibration from CuAr arc spectra.

Exposure timings at both sites are calibrated against standard clocks. The 1 or 2 second possible time calibration difference between sites has no detectable effect on the results we report.

2.1 WHT observations

We used the blue arm of the ISIS spectrograph with the R1200B grating. The CCD was read out in drift mode (Rutten et al. 1997). This allowed us to obtain spectra every 13 seconds. Observations were made over a period of 43 minutes starting at HJD = 2451676.40761 and a period of 8.349 hours starting at HJD = 2451677.39750, with short breaks for CuAr arc calibration spectra. Spectral resolution was $\lambda/\Delta\lambda = 5000$ and the spectral range was $4050 < \lambda < 4450 \text{ \AA}$. The exposure timings come from the CCD controller's clock, which is synchronized daily with the observatory's GPS-calibrated time service. The clock normally drifts about 1 second per night.

2.2 AAT observations

We used the Royal Greenwich Observatory Spectrograph with CCD readout in time-series mode (Stathakis & Johnston 1997). We obtained a spectrum every 22.5 seconds over a period of 7.272 hours starting at HJD = 2451676.97869, with short breaks every 30 minutes so CuAr arc spectra could be measured for wavelength calibration. Using the 82 cm camera and the R1200B grating gave a spectral resolution of $\lambda/\Delta\lambda = 5700$ with a spectral range of $4010 < \lambda < 4410 \text{ \AA}$. The exposure timings are calibrated against the Observatory's CAMAC clock and should be accurate to within 20 ms.

3 ANALYSIS AND RESULTS

The determination of radial velocities from the spectra and the search for periods in the velocity variations followed the method outlined by Jeffery & Pollacco (2000) using IDL programs.

Wavelength calibrated spectra were used to determine radial velocity changes of PG 1605+072. As the spectral

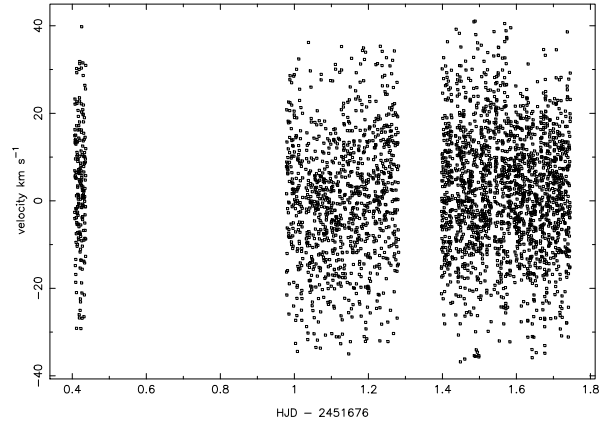


Figure 1. Radial velocities measured for PG 1605+072.

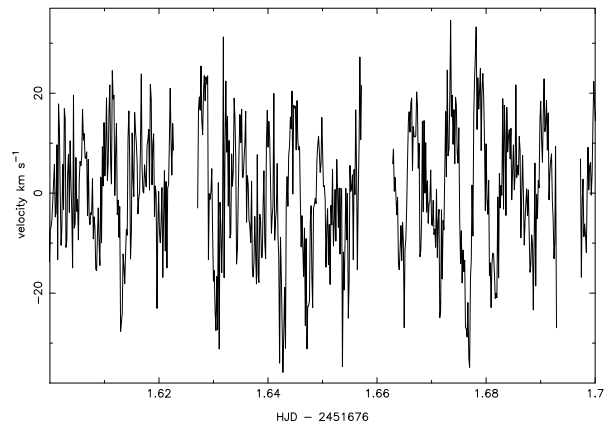


Figure 2. Expanded section of the radial velocity curve.

wavelength coverage from the two telescopes was slightly different, data from each site were treated separately to simplify the analysis. For each site's data set the mean spectrum was used as the cross-correlation template. The velocity for each spectrum was determined by fitting a Gaussian to the peak of the cross-correlation function. The templates from the two data sets were cross-correlated to allow a correction to be made to put the data sets on the same zero-scale. The velocity data is shown in Fig. 1. The velocity variations can be clearly seen in an expanded portion of the velocity curve shown in Fig. 2 (as can the gaps in the data due to the need to take wavelength calibration arcs).

A search for periods in the velocity variations was performed with a discrete Fourier transform analysis. Fig. 3 shows the periodograms for the separate velocity data sets and our complete data set, and the major photometric frequencies found by Kilkenney et al. (1999) (from their Table 2). The window function for our data is shown in Fig. 4.

The four major peaks present in the AAT and WHT data become double peaks when the data is combined. This raises the question of whether the peaks are real or the result of aliasing and if the doubling is due to aliasing, which peaks are the real ones? The separation of the peaks in the pairs is

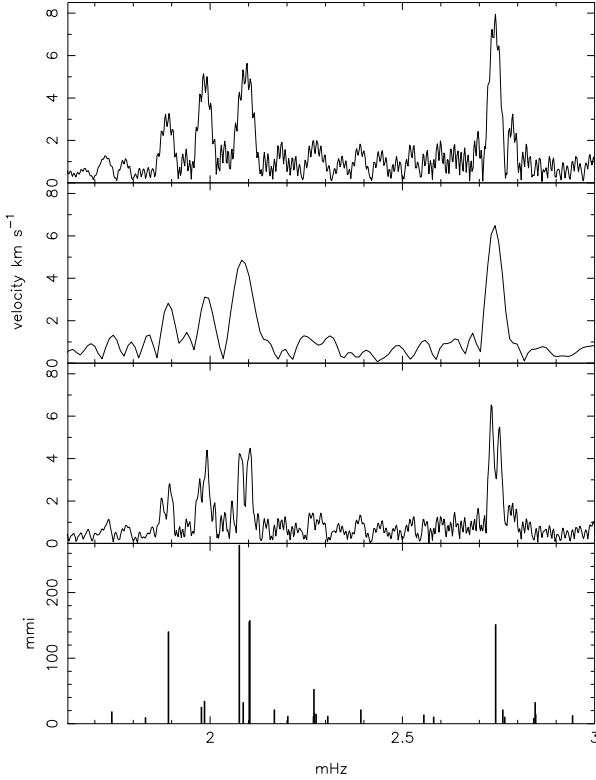


Figure 3. Periodograms for WHT, AAT, and complete data sets are shown in the top, second, and third panels, respectively. The frequencies and relative strengths of peaks found in the photometry periodogram by Kilkenney et al. (1999) are shown in the bottom panel.

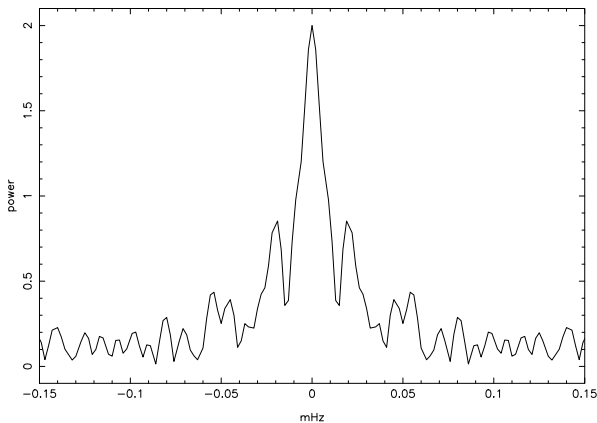


Figure 4. Window function for combined AAT and WHT data set.

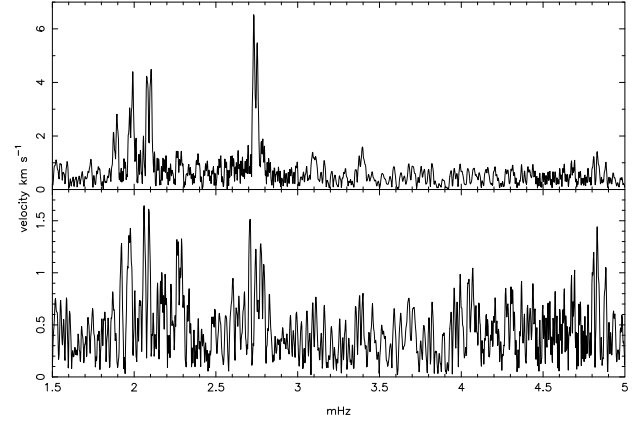


Figure 5. Periodogram before (top) and after (bottom) pre-whitening by removing the six strongest frequency peaks. Note the difference in vertical scale between panels.

between 0.019 and 0.028 mHz. The side lobes in the window function are 0.021 mHz (corresponding to about 13.2 hours) from the central peak. Aliasing is thus a possibility. However, the peak patterns do not resemble that of the window function. The power spectrum and window function of the data set without the WHT data from the first night, the small set near $\text{HJD} - 2451676 = 0.4$, are virtually identical to those of the full data set, with slightly broader but equally separated peaks. When doing pre-whitening as discussed in the following paragraph we tried removing peaks in different orders or with the photometric frequencies and no method removed the second peaks. Further, neither peak near 2.7 mHz is at the frequency found using photometry. Trials using single and multiple sine waves sampled at the observation times, with and without noise, reproduced the window function at the input frequency(ies) as expected. We admit the possibility that the 2.731 and 2.753 mHz peaks are due to aliasing, but will proceed with the analysis assuming that the splitting is real.

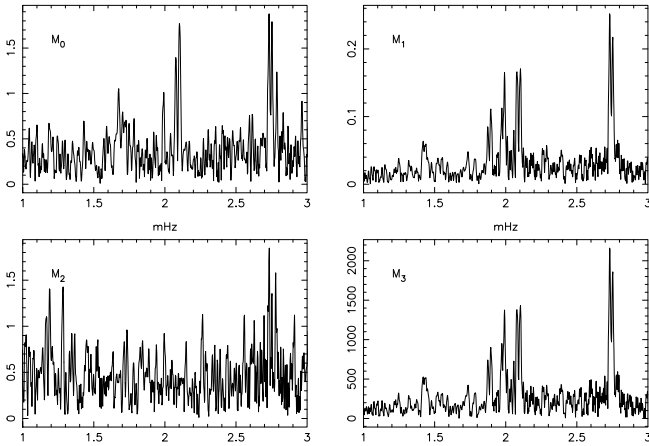
To help determine the relative strengths of the peaks in the periodogram and to detect peaks which are present only because of aliasing, we “pre-whitened” the data by subtracting successive sine waves from the velocity curve to remove individual peaks. The phase for each sine wave was found by cross-correlation with the velocity curve. The velocity amplitudes for the sine waves which remove the periodogram peaks most cleanly were found by simple trial and error. The original periodogram and the periodogram with the six strongest peaks removed are shown in Fig. 5. The frequencies and velocity amplitudes of the removed peaks are listed in Table 1. No correction has been made for projection effects. The frequency uncertainty was derived using

$$\delta\omega = \frac{3\pi\sigma_N}{2(N_0)^{1/2}TA}$$

where A is the amplitude, σ_N^2 is the variance of the noise after the signal has been removed, T is the length of the data set, and N_0 is the number of velocity data points (Kovács 1981; Horne & Baliunas 1986). The periodogram of pre-whitened velocity data in Fig. 5 looks similar to the pre-whitened photometric data in Fig. 3 of Kilkenney et al.

Table 1. Frequencies, periods, and velocities of periodogram peaks as found while pre-whitening (in order removed).

f mHz	Δf mHz	P sec	v km s ⁻¹
2.731	0.001	366.2	6.1
2.753	0.003	363.2	3.0
2.104	0.002	475.3	4.0
2.076	0.002	481.7	3.9
1.992	0.002	502.0	3.9
1.897	0.003	527.1	2.7

**Figure 6.** Moments of the cross correlation function.

(1999), with additional peaks obvious between 1.8 and 3 mHz. Peaks seen in the photometric data around 4.1 and 4.8 mHz are probably also present in the velocity data.

One useful method of mode identification for pulsating stars involves measuring the moments of the line profiles (Balona 1986; Aerts 1996). While we are not yet ready to perform such a test, PG 1605+072, with the largest pulsation amplitudes known for any sdBV, is an ideal subject to test whether the moments can be determined for any of the class. We used the cross correlation function to approximate the average line profile. For our spectra this is dominated by the strong H γ and H δ Balmer lines. An IDL routine was used to find the moments M_0 , M_1 , M_2 , and M_3 , and find their Fourier transforms. The transforms are shown in Fig. 6. The 0th moment corresponds to the equivalent width of the line. The first is the line centroid. The second is the skewness or lack of symmetry. The third is the kurtosis, a measure of how sharply peaked the line is.

The shape of the Fourier transform of the centroid, M_1 , is virtually identical to that of the radial velocity. However, the peak amplitudes for the centroid are much smaller than those of the velocities. We thought that this may happen because the hydrogen line wings are not affected as strongly by the pulsations as are weak lines or hydrogen line cores. (Our velocities come from fits to the central peak of the cross correlation function while the centroid measures the centre of the entire “line.”) To test this, we created synthetic spectra for PG 1605+072 forced to pulsate at various frequencies and modes using the programs BRUCE and KYLIE (Townsend

1997a; Townsend 1997b). When the spectra included the H γ and δ lines we found the peak amplitudes for M_1 similarly reduced in comparison with those of the velocities. When the H line regions of the synthetic spectra were eliminated and the analysis was repeated, the M_1 and velocity amplitudes were comparable, indicating that the relatively immobile H line wings were the cause of the much smaller amplitudes found using M_1 .

The close match between the shapes of the M_3 and M_1 Fourier transforms indicates that the “peakiness” of the cross correlation function, which is dominated by the hydrogen line shape, varies with periods and relative amplitudes identical to the velocity variations.

The M_0 and M_2 transforms both show peaks at some of the frequencies present in the M_1 and M_3 transforms, but with different amplitude ratios. This shows that the line equivalent widths and asymmetries vary differently than the velocity or line kurtoses.

4 DISCUSSION

It is difficult to compare our velocity amplitudes with the photometric amplitudes found by other authors, as there appears to be some shifting of pulsation frequencies. For example, the strong peaks in our velocity periodogram at 2.731 and 2.753 mHz do not correspond well with the peaks in that frequency region in the photometric periodogram of Kilkenney et al. (1999), where there is one strong peak at 2.743 mHz and several much weaker peaks, none of which are at the velocity peak frequencies. But still, in both the velocity and photometry periodograms the major peaks appear in the same general frequency regions: around 1.9, 2.0, 2.1, 2.7, and perhaps 2.3 mHz.

In addition, Kilkenney et al. (1999) say that some frequencies may have variable amplitudes (and that some of the small-amplitude peaks in the power spectrum may be artifacts due to this variability). This amplitude variability may be apparent when our velocity data and the Kilkenney et al. data are compared. The strongest peak in the velocity data is near 2.7 mHz while the strongest in the photometry data is near 2.1 mHz. The velocity data from O’Toole et al. (2000) appear to show amplitude ratios in their periodogram similar to those found in the Kilkenney et al. photometric data, though their relatively slow repetition rate (> 1 minute per exposure) and the complicated window function for the O’Toole et al. data make the comparison uncertain.

Our observations of PG 1605+072 took place about three years after the multi-site photometric campaign to observe it by Kilkenney et al. (1999) and about 2 years after the O’Toole et al. (2000) spectroscopic campaign. The peak amplitude ratio differences we find are probably due to shifts of power between the major peaks. Pulsation modes with different ℓ and m numbers can produce peaks with different amplitude ratios for velocity and photometric variations, but are unlikely to produce the large differences we find. A campaign of simultaneous spectroscopic and photometric observations would eliminate the possibility of power shifts between modes over the time period between obtaining the two types of data. In addition, the longer observing runs and wider physical distribution available for the smaller tele-

scopes used for photometry would help reduce the aliasing problem present with short, spectroscopy-only programs.

Such a simultaneous campaign would also provide a better chance at successful mode identification. With modes identified, estimates of stellar radius and luminosity can be made using Baade-Wesselink and related techniques discussed by Stamford & Watson (1981).

Mode identification may also be aided by continuing long-term observations of PG 1605+072. The rate of period change for the observed pulsations is slow enough, $dP/dt \sim 1.3 \times 10^{-12} \text{ss}^{-1}$ (Kilkenny et al. 1999), that the shifts in period we observe for the 2.7 mHz peaks are too large to be the result of the frequency of a single mode changing. If the shifts are not an artefact of aliasing, they are probably the result of shifting of power between modes very closely spaced in period, perhaps different components of a multiplet. The splitting is about the right size for this: the frequency difference between modes with successive m values is $\delta\nu \approx \nu_{\text{rot}} \frac{1}{\ell(\ell+1)}$, where ν_{rot} is the star's rotational frequency. If we guess that the 2.7 mHz peaks are due to $\ell = 1$, $m = 0, \pm 1$, where the two peaks we find with the velocity data being $m = \pm 1$ and the peak found with 1997 and earlier photometric data being $m = 0$, then $\delta\nu = 0.011 \pm 0.002$ mHz, which corresponds to a stellar rotational period of 12.6 ± 2.8 hours, not far outside the $\Pi < 8.7$ h determined by Heber et al. (1999). (We are not arguing that this is an $\ell = 1$, $m = 0, \pm 1$ triplet, but rather just that the splitting is about the size expected for rotational splitting in general for PG 1605+072.) If over time the type of multiplet can be identified (i.e. triplet, quintuplet, etc.) this would greatly aid in identifying the pulsation modes. Identifying the pulsation modes would allow analysis of the star using asteroseismology, providing more precise and accurate estimates of its physical properties.

5 CONCLUSIONS

Our two-site campaign of high speed spectroscopic observations of the variable subdwarf B star PG 1605+072 with 4-m class telescopes provides a new measurement of its radial velocity variations due to pulsation. We find pulsations frequencies similar but not identical to those found in earlier photometric studies. The relative strengths of the frequency peaks in the power spectrum for our data are different from those in the photometry data and possibly from those in an earlier spectroscopic study. The differences in peak strengths and the small differences in detected frequencies probably reflect shifts of power between pulsation modes.

A multi-site campaign of simultaneous photometric and spectroscopic observations combined with continued long-term observations should provide the best chance to identify the star's pulsation modes. With the modes identified, asteroseismology can be used to accurately determine the star's physical properties, which will be useful in modeling its evolutionary history.

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